Satellite Eötvös Test of the Weak Equivalence Principle for Zero-point Vacuum Energy

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Abstract

An Eötvös experiment to test the weak equivalence principle (WEP) for zero-point vacuum energy is proposed using a satellite. Following the suggestion of Ross for a terrestrial experiment of this type, the acceleration of a spherical test mass of aluminum would be compared with that of a similar test mass made from another material. The estimated ratio of the zero-point vacuum energy density inside the aluminum sphere to the rest mass energy density is $\sim 1.6 \times 10^{-14}$, which would allow a 1% resolution of a potential WEP violation observed in a satellite mission test that had a baseline sensitivity to WEP violations of $\sim 10^{-16}$. An observed violation of the WEP for vacuum energy density would constitute a significant clue as to the origin of the cosmological constant and the source of dark energy, and test a recently proposed resolution of the cosmological constant problem, based on a model of nonlocal quantum gravity and quantum field theory.

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A recent proposal to resolve the cosmological constant problem was based on a nonlocal quantum gravity theory and quantum field theory [1, 2]. The resolution demands that there exist a fundamental low-energy gravitational energy scale, $\Lambda_{\text{Gvac}} \sim 10^{-3}$ eV, above which the coupling of gravitons to vacuum energy density was suppressed by a nonlocal gravitational form factor in the calculation of standard model vacuum polarization loop graphs. This would require a strong violation of the weak equivalence principle (WEP) for coupling of gravitons to pure vacuum energy loop graphs compared to ordinary matter.

It is generally believed that a solution to the cosmological constant problem could alter in a significant way our understanding of gravitation and particle physics [3]. There is mounting observational evidence [4] that the universe is accelerating and that a form of dark energy exists. A small cosmological constant corresponding to a vacuum energy density $\rho_{\text{vac}} \sim (2.4 \times 10^{-3}\,\text{eV})^4$ could explain the acceleration of the universe.

We can define an effective cosmological constant

$$\lambda_{\text{eff}} = \lambda_0 + \lambda_{\text{vac}}, \tag{1}$$

where λ_0 is the "bare" cosmological constant in Einstein's classical field equations, and λ_{vac} is the contribution that arises from the vacuum density $\lambda_{\text{vac}} = 8\pi G \rho_{\text{vac}}$. Already at the standard model electroweak scale $\sim 10^2$ GeV, a calculation of the vacuum density ρ_{vac}, based on local quantum field theory, results in a discrepancy of order 10^{55} with the observational bound

$$\rho_{\text{vac}} \leq 10^{-47}\,(\text{GeV})^4. \tag{2}$$

This results in a severe fine-tuning problem of order 10^{55}, since the virtual quantum fluctuations giving rise to λ_{vac} must cancel λ_0 to an unbelievable degree of accuracy. This is the "particle physics" source of the cosmological constant problem.

A model of nonlocal quantum gravity with the action $S = S_G + S_M$ was presented in ref. [1] with the gravitational action $(\kappa^2 = 32\pi G)^3$:

$$S_G = -\frac{2}{\kappa^2} \int d^4x \sqrt{-g} \left\{ R[g, \mathcal{G}^{-1}] + 2\lambda_0 \right\}. \tag{3}$$

The matter action S_M for the simple case of a scalar field ϕ is given by

$$S_M = \frac{1}{2} \int d^4x \sqrt{-g}\, \mathcal{G}^{-1} \left(g^{\mu\nu} \nabla_\mu \phi \mathcal{F}^{-1} \nabla_\nu \phi - m^2 \phi \mathcal{F}^{-1} \phi \right). \tag{4}$$

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[3]A paper is in preparation in which more complete details of the model will be provided.

Here, $\mathcal{G}$ and $\mathcal{F}$ are nonlocal regularizing, *entire* functions and ∇_μ is the covariant derivative with respect to the metric $g_{\mu\nu}$. We chose the covariant functions

$$\mathcal{G}(x) = \exp\left[-\mathcal{D}(x)/\Lambda_G^2\right], \tag{5}$$

$$\mathcal{F}(x) = \exp\left[-(\mathcal{D}(x) + m^2)/\Lambda_M^2)\right], \tag{6}$$

where $\mathcal{D} \equiv \nabla_\mu \nabla^\mu$, and Λ_G and Λ_M are gravitational and matter energy scales, respectively.

A calculation of the first-order vacuum polarization tensor $\Pi^{\mathrm{Gvac}}_{\mu\nu\rho\sigma}$ for the coupling of gravitons to a loop consisting of photons yields for the vacuum energy density

$$\rho_{\mathrm{vac}} \sim M_{\mathrm{PL}}^2 \Pi^{\mathrm{Gvac}}(p) \sim \Lambda_{\mathrm{Gvac}}^4. \tag{7}$$

If we choose $\Lambda_{\mathrm{Gvac}} \leq 10^{-3}$ eV, then the quantum correction to the bare cosmological constant λ_0 is suppressed sufficiently to satisfy the observational bound on λ, *and it is protected from large unstable radiative corrections.*

This provides a solution to the cosmological constant problem at the energy level of the standard model and possible higher energy extensions of the standard model. The universal fixed gravitational scale Λ_{Gvac} corresponds to the fundamental length $\ell_{\mathrm{Gvac}} \leq 1$ mm at which virtual gravitational radiative corrections to *pure* vacuum energy are cut off. However, it is postulated in the model that gravitons coupled to ordinary matter have a form factor that is controlled by the energy scale, $\Lambda_{GM} = \Lambda_M \sim 1-10$ TeV, which avoids any measurable violation of the WEP for gravitons coupled to ordinary matter and guarantees that the calculations of standard model diagrams agree with experiment. This would lead to a strong violation of the WEP for coupling of low energy gravitons to pure zero-point vacuum energy compared to the coupling to ordinary matter.

To explore the possibility that the cosmological constant arises from zero point energy, Ross [5] has suggested a novel scenario in which the violation of the WEP that would result from such an effect might be observed in an Eötvös experiment. In his proposal, the acceleration of a spherical test mass of aluminum would be compared with that of a similar test mass made from another material (e.g., a monel metal like copper or silver). He chose aluminum because it has a relatively sharp transition from reflectance to absorption of electromagnetic waves at photon energies of approximately 15.5 eV. His analysis indicated that the magnitude of the missing zero-point

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energy density inside aluminum is given by

$$\mathcal{E} = \frac{4\pi}{(\hbar c)^3} \int_0^{E_{\max}} E^3 dE, \tag{8}$$

where $E_{\max}$ is the energy at which aluminum becomes transparent. For $E_{\max} = 15.5$ eV, one obtains $\mathcal{E} = 2.37 \times 10^{19}$ eV/cm^3. The rest mass energy density is 1.52×10^{33} eV, so he found that the ratio of the zero-point energy density inside the aluminum sphere to the rest mass energy density is 1.6×10^{-14}. Therefore, if comparisons were made between test masses of aluminum and, e.g., copper, a violation of WEP at approximately this level should be observed if the zero point energy does not couple to the gravitational field. Such an experiment would be a direct test of the role that a purely quantum mechanical effect plays in general relativity [6].

In a long series of elegant experiments with rotating torsion balances, the *Eöt-Wash* Group has searched for composition dependence in the gravitational force via tests of the universality of free fall. In terms of the standard Eötvös parameter η, they have reached sensitivities of $\eta \sim 1.1 \times 10^{-12}$ in comparisons of the accelerations of Be and Al/Cu test masses [7] and, more recently, have resolved differential accelerations of approximately 1.0×10^{-14} cm/s^2 in experiments with other masses [8]. Drop-tower experiments now underway in Germany [9] have as their goal testing WEP at sensitivities of $\eta \sim 1 \times 10^{-13}$, and Unnikrishnan describes a methodology under study at the Tata Institute of Fundamental Research in India wherein torsion balance experiments aiming at sensitivities of $\eta \sim 1 \times 10^{-14}$ are being developed [10]

While it is not yet clear what ultimate sensitivities might be reached by terrestrial experiments of these types, it is generally accepted that significant gains in sensitivity will be made by space-based WEP experiments, and several of them are presently in various stages of planning and development. Among these are the STEP satellite [11], the MICROSCOPE experiment [12], the Galileo Galelei (GG) mission [13], and Project SEE [14]. The target sensitivities of each of them are STEP: $\eta \sim 10^{-18}$, MICROSCOPE: $\eta \sim 10^{-15}$, GG: $\eta \sim 10^{-17}$, and SEE: $\eta \sim 10^{-16}$. The first three missions are in advanced stages of planning and hardware testing, and are expected to be launched over the next few years. Project SEE is still undergoing rigorous conceptual evaluation and is not yet a scheduled mission. However, one of the significant points of interest about it is the relative simplicity of the test mass configuration: one large spherical mass and one small one undergo a

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three-body interaction with the Earth during the orbit of the capsule containing them [15]. Analysis of the small mass motion then yields measures of WEP violation, the absolute value of the Newtonian gravitational constant, and the time variation of it. Because it is still an early stage endeavor, it might be possible to incorporate into the mission schedule a test of WEP at the SEE target sensitivity using aluminum and copper test masses, in order to examine the zero-point energy coupling. This would avoid the need to design, fund and carry out a separate independent mission, which would be very difficult to justify because of the large costs. Further details about the SEE mission are given in the review by Sanders and Gillies [16].

The website http://www.phys.utk.edu/see/ provides a description of the fundamental design features of the proposed SEE mission. It is meant to be a multi-functional platform for gravitational physics experiments, providing the capability to measure the strength of the gravitational interaction between a pair of test bodies co-orbiting the Earth in a drag-free environment. The nearly identical circular orbits of the test bodies in the field of the Earth results in gravitationally-governed relative motions between them of the type predicted first by George Darwin in 1897 and exhibited in the celestial mechanics of two of the moons of Saturn [16]. When one of the masses is much smaller than the other, an analysis of the mechanics of the interaction reveals how measurements of the relative motions can lead to a determination of the absolute value of the Newtonian gravitational constant and its time-rate of change, as well as limits on violations of the weak equivalence principle. As with any high precision measurement system of this type, great care must be taken to circumvent the problems arising from competing effects, noise, and other sources of experimental uncertainty. The satellite itself provides the first line of defense, with its capsule consisting of a series of concentric cylindrical shells that serve as radiation baffles and which provide the drag-free containment for the test masses. The orbital configuration will be a sun-synchronous trajectory that keeps the capsule illuminated at all times and thus much closer to a state of constant thermal equilibrium. The large and small test masses would be nominally 500 kg and 100 g respectively, and small masses of different materials could be orbited simultaneously to make differential measurements of the type needed to search for a WEP violation. The details of the optimal orbital parameters, composition of the error budget, and thermo-mechanics of the capsule are still under development.

If the SEE mission were able to accommodate a test of the type proposed here, the level at which the WEP violation is predicted to occur, $\sim 1.6 \times 10^{-14}$,

means that a nearly 1% resolution of it would be possible within the context of the SEE interaction. In principle, this degree of resolution would not only provide a definitive statement of the presence of such an effect if it appeared at that level, but it would also allow for enough sensitivity to observe weaker manifestations of variants of the nominal prediction. The key issue in any case becomes one of maximizing the signal size and, as always, minimizing the consequences of competing effects. To accomplish the former task, a careful re-analysis of potential test mass materials should be carried out to ensure that those with maximum estimated difference in zero-point energy density are selected. This is an important point, particularly in light of possible complexities that arise in calculating the exact values of the Casimir effect cut-offs for spherical mass configurations [17].

Another concern would be one of interpreting the meaning of an unequivocal positive result. The task would be one of establishing, for instance, whether or not the signal might alternatively be due to the revelation of the presence of a long sought-for new weak force [18]. Here again, selecting the proper experimental strategy within the context of theoretical guidance would play the key role. Moreover, while the prediction of the WEP violation in [5] is based on a straightforward analysis of the vacuum energy density deficit in aluminum relative to that present in other materials, a careful re-confirmation of that interpretation will be important to establish that the level of the violation is indeed what is claimed. A significant reduction of the strength of the expected violation brought on by any reanalysis of the coupling of gravity to the difference in vacuum energy densities in the test masses might place the measurement below the reach of the SEE Mission's sensitivity. Lastly, if a satellite experiment were successful in revealing the predicted effect, physics would be faced with one additional concern: the need to repeat and independently confirm a finding of this significance. Perhaps completely new technologies for terrestrial experiments could eventually be called on to meet any such future need

As a point of historical interest, we note that one of the earliest cases where vacuum polarization effects were discussed within the context of a gravitational physics experiment was in Long's interpretation of his non-null result for a breakdown in the inverse square law of Newtonian gravity [19]. He claimed to find a scale dependence in the Newtonian gravitational constant, G and argued that a certain type of vacuum polarization process could explain his positive results. He further argued that the results consistent with no breakdown that were obtained in the null experiments of others [20]

did not invalidate his findings of a variation in G with inter-mass spacing, because of the lack of a polarizing gravitational field in such experiments. Chen [21] extended the argument and contended that vacuum polarization could even resolve the differences between the null and the non-null results via a very weak shielding mechanism that could arise from it, but the very stringent limits on gravitational shielding phenomena [22, 23] derived from recent experiments block that possibility. The present consensus is that the Newtonian inverse square law has been proven to be valid over the ranges through which it has been tested experimentally. The new laboratory searches for possible violations of it now focus on the sub-millimetric regime, and are driven largely by predictions for short-range variations in gravity that arise in extra-dimensional theories [24, 25].

We call for a satellite test of the WEP that is designed to determine if the cosmological constant arises from zero-point energy, and whether the WEP is violated for coupling of gravitons to pure vacuum energy compared to ordinary matter. An observed violation of the WEP would serve as experimental support for the conjectured resolution of the cosmological constant problem, based on a model of nonlocal quantum gravity and quantum field theory [1, 2].

Acknowledgments

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